A Class IV Flextensional Device Based on Electrostrictive Poly(vinylidene fluoride-trifluoroethylene) Copolymer

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Abstract – A class IV flextensional device based on electrostrictive P(VDF-TrFE) copolymers was fabricated and characterized. As an actuator, the small device can produce a displacement of more than 1 mm in air with high load capability. As an underwater transducer, the device can be operated at frequencies of several kilohertz with high transmitting voltage response and low mechanical quality factor. Finite element analysis was used to model the flextensional device. The modeling indicates that the performance of the flextensional transducer could be readily tailored by adjusting the parameters of the flextensional metal shell to meet the requirement of different applications.

I. Introduction

Flextensional devices including actuators and transducers act as mechanical transformers, which transform and amplify the displacement and force generated in the active element to meet the demands of different applications. Structurally, the device consists of a driving element connected to a flexible shell structure that transforms the high impedance, small extensional motion of the active element into low impedance, large extensional motion of the shell, or vice versa. Flextensional transducers are now widely used for underwater transducers [1-3]. From the different designs of the flextensional shell structure, flextensional transducers were divided into five classes [1,3]. Among them, classes IV and V have received great attention in recent years. The Moonie and Cymbal developed by Newnham et al. at the Penn State University are essentially miniaturized version of class V flextensional transducers [3-5].

In the traditional flextensional devices, i.e. Moony, Cymbal and Class IV flextensional transducers, piezoelectric ceramics are used as the driving elements [4-6], which have a strain level of 0.1%. Recently, we developed a class of electrostrictive polymers, the P(VDF-TrFE) based terpolymers and high-energy electron irradiated copolymers. In these polymers, electrostrictive strains of more than 7% have been observed with an elastic modulus of 1.0 GPa and elastic energy density of more than 0.5 J/cm^2 [7-9]. In addition, it has been shown that this new class of materials can be operated to above 100 kHz. These features make this new class of material attractive as the driving element for the flextensional devices.

In this paper, we will first briefly review the in-air and underwater experimental results of the flextensional transducers with the electrostrictive copolymer as the active element. Then the finite element analysis will be carried out to analyze the performance of the device and investigate how the performance depends on the parameters of the flextensional structure.

II. In-air and Underwater Performance

Using the electrostrictive P(VDF-TrFE) copolymer as a driving element, a flextensional transducer of class IV was fabricated and tested. This transducer consists of an active plate (area ~ 1 inch x 1 inch and thickness ~ 1-2 mm), which is in the multilayer form laminated from the electrostrictive P(VDF-TrFE) polymer films (each film thickness~30 μm), and two flextensional metal shells which were fixed at the two ends of the active polymer plate to amplify the displacement. Figure 1 shows schematically the overall configuration of the transducer, where 2d=2 mm, L=26 mm, and w=31 mm are the thickness, length and width of the multilayer electrostrictive P(VDF-TrFE) plate (EAP plate), t=0.375 mm is the thickness of the metal shell, h=3 mm is the height of the arch, respectively. δL and δh are the displacement along the X and Z directions, respectively. $\delta h/\delta L$ is the amplification ratio of the flextensional structure. The spring-steel sheets with modulus of 210GPa (Blue Tempered & Polished Spring Steel, Precision Brand Products, Inc.) were used as the metal shells.

The results of in-air characterization of the device show that this transducer has a resonance frequency at about 4.5 kHz and can generate displacement $2\delta h$ of more than 1 mm in air (the transducer total thickness is 7 to 8 mm in the same z-direction). Under different driving fields, $2\delta h$ is about 0.40 mm at 50V/μm, and the maximum displacement can reach more than 1 mm at a driving level of 90V/um.

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When operated in water, the fundamental resonance frequency of the transducer is reduced to about 1.7 kHz due to the water load. To characterize the underwater performance, the transmitting voltage response (TVR) was measured. Figure 2 shows the TVR results under two different applied DC bias fields. A broad resonance was observed which centers at 1.7 kHz. The TVR near the resonance is 123 (dB re 1 μPa/V @1m) for the device. In the frequency range from 1 kHz to 5 kHz, it was found that the transducer shows an omnidirectional pattern, due to the fact that the dimension of the transducer is much smaller than the acoustic wavelength.

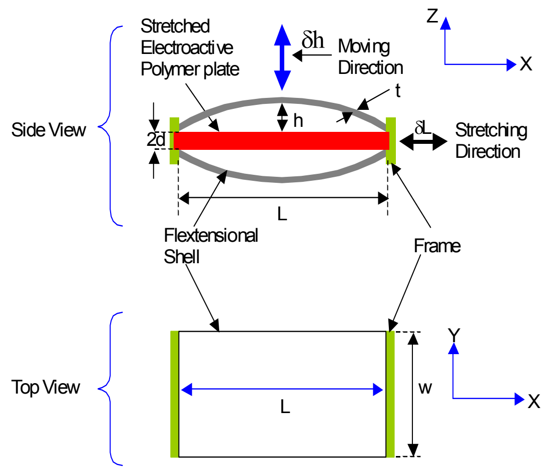

Figure 1: Sketch of flextensional transducer based on stretched electroactive polymers.

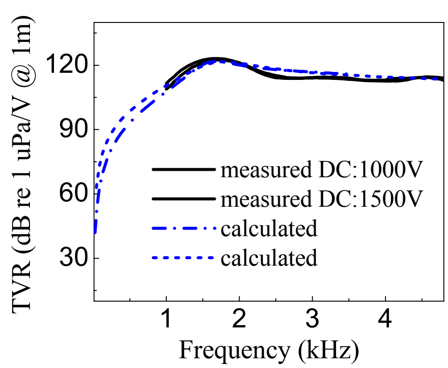

Figure 2: Measured and calculated TVR of the flextensional transducer. Solid lines are the measured values under DC bias, and the dash lines are the calculated values using FEA with different meshing levels.

III. FINITE ELEMENT MODELING OF THE TRANSDUCER

The finite element analysis (FEA) has been used extensively in modeling complex transducer and actuator performances and properties [3,5,10]. The purpose of FEA is to numerically solve complex partial differential equations so as to mathematically describe and predict the physical behaviors of an actual engineering system under various structures and loading conditions. In this study, Ansys 5.7 (Ansys, Inc., Canonsburg, PA) was used to simulate the in-air and underwater performance of the transducer. Since no commercial FEA code has been developed to model electrostrictive materials, the electrostrictive polymer was treated as an effective piezoelectric material (an electrostrictor under DC bias

field). In the FEA modeling, the in-air directly measured data were used to validate the FEA model. Then the FEA model was used to predict the transducer underwater performance.

Figure 3 shows the 3-D geometry and meshed elements created using Ansys, where the coupling field element SOLID 5 [11] was used to simulate the electroactive polymer. For the underwater modeling, 2D model was used to reduce computing time. Fig. 3 also shows the deformed shape under electrical driving. The motion of the EAP plate in the X-direction results in the amplified motion of the metal shell in the Z-direction. The FEA results show that at low frequencies, 2δh is 0.41 mm, and the δh/δL is about 1.76. At the resonance frequency of 4.5 kHz, the maximum 2δh is up to 1.6 mm. These results are consistent with experimental data.

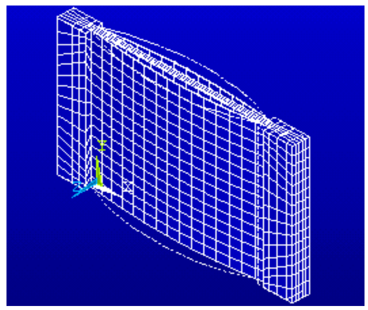

Figure 3: Meshed geometry and deformed shape of the transducer in air.

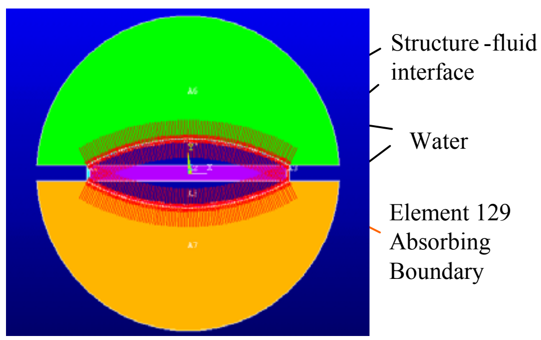

Figure 4: The geometry of the underwater model with infinite water media and structure-fluid interface.

For the underwater modeling, two semi-spheres of water with radius of 1 meter were placed in contact with the two radiating faces, as shown in figure 4, in which the water semi-sphere is not drawn in proportion in order to show the small transducer. A structure-fluid interface was defined along the out surface of the metal shell between the transducer and water. Then the semi-sphere of water was meshed using acoustic element FLUID 29 (2D). In Ansys, there are specially designed infinite acoustic elements such as FLUID 129 and FLUID 130 [11]. These infinite acoustic elements absorb the incident pressure wave, simulating the outgoing effects of a domain that extends to infinity beyond the FLUID 29 and FLUID 30 elements. By using FLUID 129 to model the outer boundary of the hemisphere of water, an infinite fluid environment was created, as schematically shown in fig. 4. After applying a voltage of one volt to the EAP plate, a harmonic analysis was carried out to determine the frequency dependent parameters, such as pressure in the water and the displacement of the transducer. The TVR was calculated and presented in fig. 2 to be compared with the experimentally measured data. The calculated TVR curve shows good agreement with the measured data, with a resonance frequency around 1750 Hz and a maximum TVR of 122 dB re 1 μPa/V @1m.

To investigate how the underwater performance of the device depends on the parameters of the flextensional metal shell, FEA was used to predict the behaviors of the flextensional transducer under different structure parameters, such as h, t and L as shown in fig.1. In this study, the parameters of EAP plate were kept as constant.

Figure 5 shows the TVR of the flextensional transducer as a function of arch height h. When h varies from 1 to 8 mm, the resonance frequency changes in a large range from 700Hz to 5.3 kHz with a TVR from 116 to 123 dB re 1 μPa/V @1m, indicating the operation frequency can be adjusted in a large range. Similarly, other parameters such as t and d can also be changed to tailor the performance of the transducers.

The results indicate that this kind of transducer can be operated at a frequency range of several hundreds of hertz to over 10 kHz with relatively high TVR (more than 115 dB re 1μPa/V @1m) by changing the parameters of the flextensional transducer. All these parameters can be utilized for the future flextensional transducer design. For instance, the results in figure 6 show that δh/δL can be adjusted from 4.5 to less than 1 by increasing the arch height h from 1 mm to 8 mm.

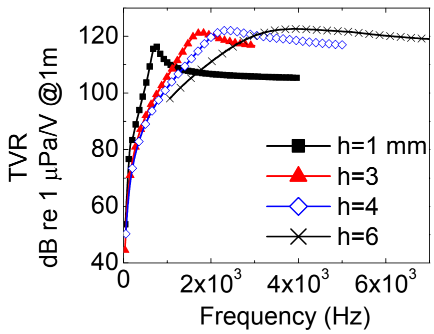

Figure 5: TVR and resonance frequency f_r of the transducer as a function of arch height h.

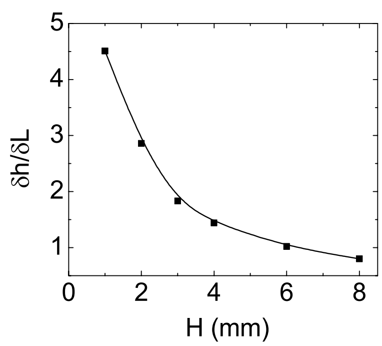

Figure 6: Amplification ratio δh/δL as a function of arch height h.

IV. Conclusions

A flextensional transducer was fabricated and tested utilizing the newly developed high electrostriction electroactive polymers. The advantages of the new polymer materials are high strain level, high elastic energy density, and lightweight. The results show that the device (1″x1″ in lateral dimension and a few mm thick) is capable of generating a displacement at mm level in air with high mechanical load capability (not shown in this paper), which is highly desirable for actuator applications. As an underwater transducer, the device exhibits a low frequency resonance (< 2 kHz) while generates a relatively high TVR of around 122 dB re 1 μPa/V @1m. The FEA modeling indicates that the performance of this flextensional transducer could be tailored over a large range by changing the parameters of the flextensional metal shell. The results show that this type of transducer can operate at the frequency range from several hundreds hertz to 10 kHz with a relatively high TVR.

V. Acknowledgements

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